Directly written monolithic waveguide laser incorporating a distributed feedback waveguide-Bragg grating

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We report the fabrication and performance of the first C-band directly written monolithic waveguide laser (WGL). The WGL device was created in an erbium- and ytterbium-doped phosphate glass host and consisted of an optical waveguide that included a distributed feedback Bragg grating structure. The femtosecond laser direct-write technique was used to create both the waveguide and the waveguide-Bragg grating simultaneously and in a single processing step. The waveguide laser was optically pumped at approximately 980 nm and lased at 1537 nm with a bandwidth of less than 4 pm. © 2008 Optical Society of America

The use of ultrafast lasers to inscribe photonic components in optical media, the so-called direct-write technique, is a research field that is attracting considerable attention. The technique enables optical waveguide devices to be written in active and passive glasses through the use of a tightly focused femtosecond laser beam that is scanned through an optical medium of interest. By translating the optical medium on computer controlled translation stages arbitrary three-dimensional waveguide designs can be rapidly fabricated. The nonlinear materials interaction processes that are strongest at the focus of the writing laser can yield a region of local positive refractive index change that forms an optical waveguide [1]. This process of nondestructive material modification is most commonly applied to amorphous glass hosts in which positive refractive index changes can often be achieved. A wide range of devices have been created using the direct-write technique, including splitters [2], interferometers [3], and gratings [4,5]. The technique has also been used to create amplifying waveguide regions that have formed the basis for waveguide lasers (WGLs); however, these devices have always relied upon fiber-Bragg gratings to act as extrawaveguide reflectors [6,7]. Nevertheless the performance of these devices is impressive, with output powers as high as 80 mW reported with slope efficiencies of 21% [6], results that exemplify the potential of the direct-write technique to create devices for integrated optical systems. In this Letter we present what is to the best of our knowledge the first report on the creation of a directly written monolithic waveguide-laser device that, unlike previous waveguide-laser designs, incorporates an intrawaveguide laser cavity mirror. This mirror was in the form of a distributed feedback (DFB) waveguide-Bragg grating (WBG) that was coherent over the length of the device. Our simple laser fabrication technique differs from previously reported and more complicated methods that required lithographic, ion-exchange, interferometric grating writing and reactive etching processes [8], combined interferometrically written WBGs and plane mirror architectures [9], or used a holographic system to create a string of non-phase-aligned microgratings [10]. DFB lasers are characterized by their narrow linewidth and single frequency output [11], and our use of this architecture well matches the capabilities of the direct-write technique with the requirements of modern integrated optical systems.

The laser used to write the WGL device was a 1 kHz repetition rate, 120 fs pulse length, 800 nm regeneratively amplified Tr: sapphire laser that was focused into the glass sample using a 20×, 0.35 effective NA microscope objective. The writing-laser beam was circularly polarized, because this polarization has been demonstrated to create waveguides with the lowest propagation losses in other host materials [12]. A slit was placed in front of the microscope objective to modify the shape of the laser focus and create circularly symmetric waveguides as reported in [13]. The glass sample was a 2% (by weight) erbium and 4% ytterbium codoped “QX” phosphate glass host (Kigre, USA) that was mounted atop an air bearing based three-axis translation stage system (resolution 4 nm, accuracy 0.75 μm from Aerotech, USA). The 20 mm long glass sample was translated at 25 μm/s through the writing-laser beam that was focused 300 μm below the surface of the glass. To create the WBG structure a similar technique to that reported in [5] was used. The writing laser was 100% intensity modulated at approximately 50 Hz with a 50:50 mark–space ratio while the glass sample was being translated, thereby creating a waveguide formed by segments of exposed glass with an approximately 500 nm pitch. This corresponded to a first-order Bragg grating structure in the glass. Modulation of the writing-laser intensity was conveniently achieved by interrupting the trigger signal to the regenerative amplifier’s Pockels cells. The pulse energy used to create the WBG based laser device was 1.6 μJ as measured after the slit. The glass sample was ground and polished back by 150 μm (at each end facet) after device fabrication to remove the distorted regions of
waveguide where the writing-laser beam entered and exited the sample. Figure 1 shows a transmission differential interference contrast (DIC) micrograph of the fabricated first-order WBG structure. The modified waveguiding region was approximately 7 μm in diameter and clearly shows a 500 nm periodic refractive index variation. The waveguide supported a single transverse mode in the C band indicating that, if assumed to be of step-index profile, the maximum refractive index difference between the waveguide and the bulk glass was $2.3 \times 10^{-3}$. The highly nonlinear interaction between the writing-laser focus and the glass material allowed the creation of the subwavelength grating features observed in Fig. 1. However, owing to the physical limit of diffraction imposed on the writing-laser-beam’s focus, the grating periods cannot be assumed to have a square-wave refractive index profile that replicates the writing-laser intensity modulation. It is more likely that the refractive index profile is approximated by a triangular-cum-sinusoidal form similar to that observed in the inset of Fig. 1, wherein a graph of the transmission-DIC micrograph intensity is shown.

The pumping and diagnostic arrangement shown in Fig. 2 was used to measure the performance of the WGL and WBG. When operating as a laser the device was double-end-pumped, using two laser diodes with 980 and 976 nm output wavelengths, while the laser output was studied using an optical spectrum analyzer (OSA) and a wavemeter. A single optical isolator connected to the 976 nm laser diode prevented interaction between the otherwise identical pump sources. The output fiber from the wavelength division multiplexers (WDMs) (Corning Hi-980) supported too small a mode-field diameter at the pump wavelength (4.2 μm) to couple efficiently to the WGL. To overcome the loss associated with this mismatch between the waveguide and fiber mode-field diameters approximately 250 μm long sections of graded index optical fiber (GIF625) were fusion spliced to the Hi-980 pump fiber tips and acted as mode-field converters in a manner similar to that reported in [14]. To facilitate stable operation of the DFB WGL an estimated $\pi/2$ phase shift was induced at the center of the WBG using a small external heater. The application of heat to create a center-grating phase shift in a fiber DFB laser device has been reported previously and enables single-longitudinal mode operation at a wavelength at the center of the Bragg grating stop band [11]. When studying the WBG characteristics the pump laser diodes were turned off and the OSA and wavemeter shown in Fig. 2 were replaced by a swept-wavelength system and a three-port circulator. The WBG reflection and transmission data were collected through the WDMs, and a refractive index matching gel was used between the fiber and waveguide facets at all times. Because the WBG resonance under test coincided with the quasi-three-level-laser erbium transition any C-band optical measurement performed on the Bragg grating was inherently subject to absorption of the probe light. Therefore measurements of the reflection and transmission efficiencies cannot be made exactly and are lower and upper bounds on these quantities, respectively. The reflection and transmission characteristics of the WBG without the thermally induced central phase shift are shown in Fig. 3; the graphs are not corrected for WDM, coupling, or the unknown waveguide propagation and absorption losses. The WBG has one sharp Bragg resonance with a FWHM of 140 pm, indicating the excellent coherence or phase stability of the grating. The transmission spectrum of the grating is characterized by material absorption losses on the long wavelength side and losses to the continuous cladding of the WBG on the short wavelength side of the Bragg resonance. In reflection the grating is characterized by weak scattering reflections at wavelengths outside of the strongly reflecting resonance peak.

The monolithic WGL device was pumped with up to 710 mW of light from 976 and 980 nm pump diodes. The maximum power from the 976 and 980 nm pump diodes at the WGL were 364 and 346 mW, respectively. The threshold pump power for lasing was

![Fig. 1. Transmission DIC micrograph of the first-order WBG. The inset shows a section of the WBG at 3× magnification. Overlaid on the inset is a graph of the grating image intensity.](image1)

![Fig. 2. Waveguide laser pumping and diagnostic setup.](image2)

![Fig. 3. Reflection and transmission spectra of the unpumped waveguide-Bragg grating.](image3)
639 mW, and the maximum recorded output power from the WGL device was 0.37 mW (the summed output power emitted symmetrically from each output facet). The output power of the WGL was limited by and increased monotonically with the applied pump power. The output from the WGL observed with a 10 pm slit-width OSA is shown in Fig. 4. The WGL output spectrum displays a single peak in intensity with a width that is limited by the instrument’s resolution and a greater than 50 dB side-mode suppression ratio (SMSR). The laser wavelength measured by a scanning Michelson wavemeter was 1537.627 nm, and the same instrument provided an estimate of the maximum laser linewidth (based on coherence length) of 4 pm. The center laser wavelength was stable to ±3 pm over a measurement period of 5 min, and the source of this drift was expected to be due to variations in the temperature of the waveguide structure induced by changing laboratory environmental conditions. The narrow linewidth output, good wavelength stability, and high SMSR make this WGL a suitable source for dense wavelength division multiplexing applications. The wavelength of this design of laser is specified by the period of the WBG (subject to the gain-bandwidth constraints of the host material) and the refractive index of the medium. Measurements of the reflection spectra from WBGs written with known periods indicate that the refractive index of the host material used in this study was 1.5398 at 1535 nm and 1.5391 at 1560 nm. Given these data WGLs created using our technique could be easily aligned with the 100 to 25 GHz International Telecommunications Union (ITU) frequency grids. Furthermore it is expected that the WGL wavelength could be thermally tuned (by the laser d\lambda/dT) would be determined by the host material’s coefficient of optical path length with temperature.

This Letter is the first report of a directly written monolithic WGL and of the meaningful integration of two direct-write platforms, namely, a WBG and an amplifier, to form a genuinely integrated photonic device. Our technique for creating these devices is extremely flexible and enables the creation of narrow linewidth lasers in bulk optical materials without the need for external components. A simple computer code controls the laser, translation stage system, and frequency generator used for creating the WBG. The ratio of the sample translation speed to the writing-laser modulation frequency controls the WBG period, and we expect that the grating reflectivity could be adjusted using the technique described in [5] where the mark–space ratio of the modulation square wave applied to the writing-laser modifies the grating period contrast. This technique for WGL fabrication is applicable to all doped glass hosts that can be femtosecond-laser processed to create a waveguiding region and is limited only by the period of the shortest wavelength grating that can be realized in this fashion. The resulting devices are naturally compatible with existing waveguide devices such as splitters, amplifiers, and interferometers. The relatively high threshold power (as compared to WGLs based on extrawaveguide cavity mirrors), and low optical efficiency of this WGL indicates that there is potential to improve the performance of the device by refining the WBG grating characteristics, improving the mode coupling between the WGL and launch fibers and optimizing the active device length and dopant concentrations. Further device investigations will include measurements of the laser relative intensity noise, Fabry–Perot interferometer analysis of the laser spectrum and further WBG characterization.

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References